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METHODS OF DECREASING THE TIME CONSTANT OF INPUT CIRCUITS OF ELECTROMETRIC AMPLIFIERS /88*

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ABSTRACT

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Two methods of compensation are described for the transient characteristics of electrometric amplifiers - negative feedback with a compensating filter and positive feedback. Both methods make it possible to obtain approximately the same rise time for the signal at the output. The reasons which limit the decrease in the rise time and the possibilities of their elimination are discussed. Author

Introduction

Electrometric amplifiers are usually applied to measure small currents which vary slowly with time. The typical values for the input impedance of electrometric amplifiers with negative feedback and a large amplification factor in the feedback loop are $K - R = 10^{11}$ to 10^{12} ohm, shunted by a capacity

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*Numbers given in the margin indicate the pagination in the original foreign text.

$C = 0.2\text{-}0.1$ pf. In this case the time constant of the input circuit $\tau = R[C + C_{in}/(1 + K)] \approx RC$ cannot be made less than 10 to 200 sec, which corresponds to a pass band of 0 to 1-20 cps for the input circuit. Recently, in connection with a series of new problems in the field of mass-spectrometry, biology and other fields, it has become necessary to measure more rapid processes by means of electrometric amplifiers. It becomes necessary to lower τ to a few milli-seconds, i.e., to increase the band width to several hundred cycles.

It is not desirable to decrease the time constant by decreasing R because, in this case, the sensitivity of the amplifier is lowered. The capacity of the input circuit of electrometric amplifiers with negative feedback (even when the gain K is very high) cannot be lowered below the natural distributed capacity of the resistance R. The minimum values of this capacity are 0.1 to 0.2 pf; therefore, if a further decrease in the time constant of the input circuit of electrometric amplifiers is desired, it is necessary to compensate for the transient (frequency) characteristics either by using a compensating filter in the negative feedback loop (refs. 1, 2) or by introducing additional positive feedback (refs. 3-6).

1. Compensation in the Negative Feedback Circuit.

A schematic diagram of an electrometric amplifier with a compensating filter in the negative feedback loop (figure 1) has been described as early as 1952 (ref. 1). Compensation is achieved by an increase in amplification as the total input impedance is decreased. As we can see from figure 1, in the region of low frequencies, where $1/\omega C_{in} \gg R$ and $1/\omega C_K \gg R_K$, the negative feedback is almost 100 percent when the gain in the feedback loop is $K \gg 1$ and the gain with the feedback is $K' = -K/(1 + K) \approx -1$. At high frequencies when $1/\omega C_{in} < R$ and

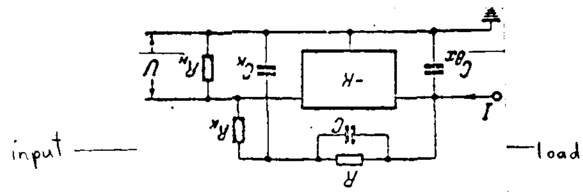

Figure 1. The principal scheme for the compensation of an electrometric amplifier by means of a filter in the negative feedback loop.

$1/\omega C_K < R_K$, the percentage of negative feedback decreases and the gain K' increases in absolute value compensating the decrease in the input impedance.

The basic characteristic of an electrometric amplifier is not the voltage gain but is the sensitivity to current which is equal to the ratio of the output voltage U to the input current I. For the network in figure 1 the sensitivity to current in the frequency function is equal to:

$$\dot{\rho}(\omega) = \dot{U}/\dot{I} = \\ = \frac{KR(1 + j\omega\tau_K)}{1 + K + j\omega(\tau_K + \tau_\Sigma + K\tau) - \omega^2\tau_K\tau_\Sigma},$$

where $\tau_K = R_K C_K$, $\tau_\Sigma = R(C + C_{in})$, $\tau = RC$. In deriving this expression it is assumed that K does not depend on the frequency in the range from 0 to 1 kc and that the output load resistance is $R_L \ll R$.

The expression for $\dot{\rho}$ may be simplified since we can neglect the quantities /89
τ_K and τ_Σ compared with $K\tau$. Indeed, usually $K > 10^3$, $C \approx 0.2$ pf and $C_{in} \lessapprox 20$ pf. Consequently, $K\tau \gg \tau_\Sigma$ or $KC \gg C + C_{in}$. If $C_{in} > 20$ pf, then to decrease its effect it is necessary to increase K. To provide compensation the condition $\tau_K \approx \tau$ must be observed so that we may let $\tau_K + \tau_\Sigma + K\tau \approx K\tau$ and $K \gg 1$. Then

$$\dot{\rho}(\omega) \approx \frac{R(1 + j\omega\tau_K)}{1 + j\omega\tau - \omega^2 K^{-1}\tau_K\tau_\Sigma}.$$

The transient characteristic of the circuit which is determined as the response to an input current which has the form of a unit pulse, may be obtained by the operational method if we replace $j\omega$ by p and $\dot{I}$ by I_0/p:

$$\rho(t) = U(t)/I_0 = R(\tau_K/\tau)[(1 - e^{-t/\tau_\sigma}) + (\tau/\tau_K - 1)(1 - e^{-t/\tau_M})].$$

The transient process consists of the sum of two exponents (fast and slow) with a time constant $\tau_\sigma \approx \tau_\Sigma \tau_K/K\tau \ll \tau$ and $\tau_M \approx \tau$. If the time constant of the compensating network is made equal to the time constant of the input circuit without compensation, then the second term in the expression for $\rho(t)$ becomes equal to zero and

$$\rho^*(t) = R(1 - e^{-t/\tau_\sigma}).$$

Consequently, when $\tau_K = \tau$, the transient characteristic of the compensated amplifier represents an exponential curve with a small time constant

$$\tau_\sigma^* = \tau_\Sigma K^{-1} = R(C_{BX} + C)K^{-1} \ll \tau.$$

It is obvious that as K becomes larger, τ_σ^* becomes smaller; however, the increase in K is limited by the frequency range within which K is almost independent of the frequency. For example, for $K = 10^4$, $R = 10^{11}$ ohm and $C_{in} + C = 20$ pf, $\tau_\sigma^* \approx 0.2$ milli-sec, $f_{0.7} = 1/2\pi\tau_\sigma^* \approx 800$ cps. In this band, K must be independent of the frequency, while outside its limits the rate of drop of the frequency characteristic $K(\omega)$ must be not more than 6 db per octave. We should note that the equivalent input capacity of the amplifier in this example is negligibly small: $C_{equi} = \tau_\sigma^* R^{-1} = 2 \cdot 10^{-4}/10^{11} = 0.002$ pf.

The experimental investigation of compensation was carried out with a bread-board model of the electrometric amplifier using subminiature vacuum tubes with 100 percent negative feedback and a gain of $K = 700$ in the feedback loop. This gain was independent of frequency up to approximately 500 cps. The input capacity of the amplifier without feedback was $C_{in} = 5.5$ pf. Tests were conducted using different values and different types of high megohm resistances R in the feedback loop. The experimental setup is shown in figure 2. Saw-tooth oscillations from a generator with low output impedance and good linearity were fed to the input of the amplifier through a small capacity $C_0 \approx 0.5$ pf with an air dielectric. Due to the differentiation of the saw-tooth voltage by the network $R/(1 + K) - C_0$ the current I in the input circuit was of a strictly rectangular shape (the error in differentiation was $C_0/C(1 + K) < 1$ percent). The output voltage was observed by means of a D. C. oscilloscope. The frequency of the input saw-tooth voltage could be varied from 0.01 to 100 cps, which made it possible to observe in detail the front as well as the flat part of the transient process. In addition to the transient characteristics, the frequency characteristics of the amplifier were also recorded by feeding a sinusoidal current to the input in the frequency range 0.1 to 100 cps. The value of the current was determined from the known capacity by using the expression $|\dot{I}| = E\ |j\omega C_0|$.

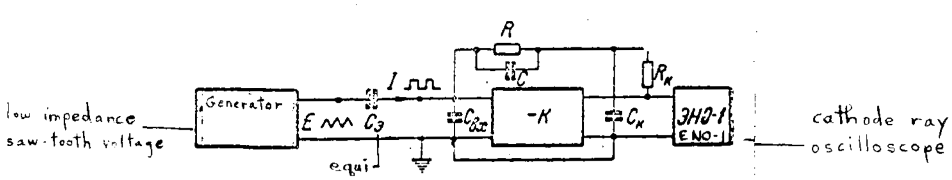

Figure 2. A schematic diagram for investigating the transient processes in electrometric amplifiers with compensation.

The results of the test are shown on table 1. Figure 3 shows the most characteristic form for the oscillogram of the transient process. From figure 3a we can see that the transient characteristic when we maintained design condition for compensation $\tau_K = \tau$ is distorted. By decreasing τ_K the characteristic becomes more smooth; however, in this case the rise time increases. When $\tau_K = (0.5\text{-}0.4)\tau$ (figure 3b), the characteristic does not have an inflexion, while the rise time, which is determined as the time during which the voltage achieves a value of 0.63 U_{max} ($Ut_{front} = U_{max}{}^{e-1}$), increases compared with figure 3a by /90
a factor of approximately 1.5. Table 1 shows the minimum rise time for the characteristic without inflexion. From Table 1 it follows that:

1. The natural capacity of the feedback loop C depends on the type of high megohm resistance. For resistances KLM $C \approx 0.2$ pf, while for KVM it is twice as small;

2. The rise time of the output voltage in the presence of compensation also depends on the type of resistance. For example, for two almost identical values $R \sim 10^{12}$ ohm the values of t_{front} differ by a factor of 1.4;

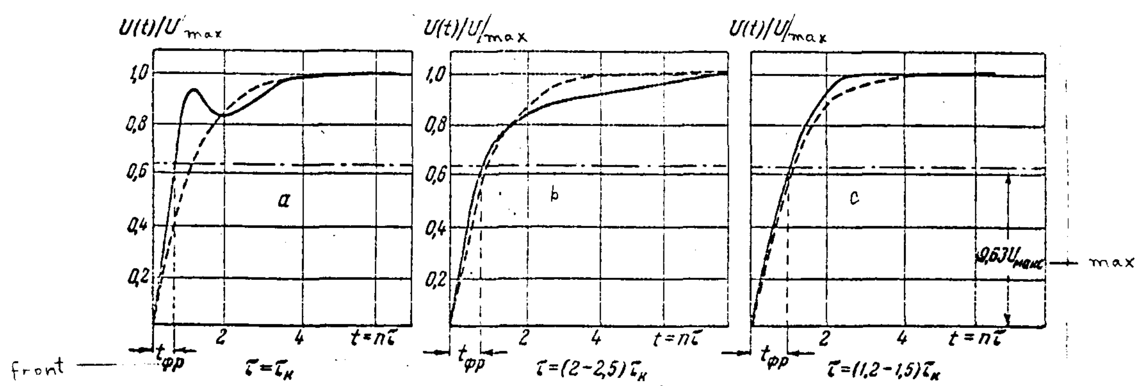

Figure 3. Experimental (solid lines) and design (broken lines) curves for the transient processes in the electrometric amplifier for various perameters of the compensation network.

TABLE 1

R, ohm	Type of resistance	Without compensation: τ, milli-sec	Without compensation: $f_{0.7}$, cps	Without compensation: $C = \tau/R$, pf	With compensation in the negative feedback circuit: R_K, megohms	τ_K, milli-sec	τ/τ_K	t_{front}, milli-sec	$f_{0.7}$, cps	$C_{equi} = t_{front}/R$ in pf	Must be for $\tau=\tau_K$: $\tau^*_\sigma = \tau_\Sigma/K$, milli-sec	t_{front}/τ^*_σ	Compensation with additional capacity: C_D, pf	t_{front}, milli-sec	$f_{0.7}$, cps
$4 \cdot 10^{10}$	KLM	4	40	0.10	1.3	1.3	3	1.8	90	0.045	0.3	6	—	—	—
$1 \cdot 10^{11}$	KVM	20	8	0.20	0.56	8.4	2.5	3.5	46	0.035	0.8	4.5	2500	3.8	41
$9 \cdot 10^{11}$	KVM	240	0.7	0.25	1.2	120	2	60	2.5	0.055	7.5	8	7000	50	3.2
$1 \cdot 10^{12}$	KLM	85	1.9	0.085	0.8	24	3.5	46	3.5	0.045	8.0	5.5	—	—	—
$1 \cdot 10^{11}$	KVM	18	9	0.18	0.2	0.5	36	15	10.5	0.15	2.0	7.5	750	1.5	150

3. For all resistances R the rise time t_{front} turns out to be greater than the computed time constant τ_{σ} BY A FACTOR OF 5 TO 6. If the condition for compensation $\tau_K = \tau$ were observed, t_{front} would decrease only by a factor of 1.5 to 2.

One of the possible reasons for the discrepancy between design values and experimental values is that the capacity of the feedback loop C is not lumped but is distributed. To decrease its effect Pelchowitch (ref. 1) proposed that the capacity of the feedback loop be increased by placing a special lumped capacity of approximately 1 to 2 pf, parallel to the resistance R. However, detailed investigations have shown that it is undesirable to increase the capacity C. In the first place when we increase C the input impedance of the amplifier is decreased in the region of high frequencies which leads to a deterioration of the signal-to-noise ratio. In the second place when the compensation condition $\tau_K = \tau$ is not closely observed a small but very slowly damped component $1-e^{-t/\tau_M}$ appears in the transient process. The greater the capacity C, the greater is $\tau_M \approx \tau$. The experimental verification of compensation with an increased value of the capacity C has shown that even with the most careful selection of the quantity τ_K the transient characteristics always have a noticeable slowly rising region (figure 4). The condition $\tau_K = \tau$ cannot be /91 satisfied precisely since the transient process in the amplifier without compensation is not exponential (figure 5). Consequently $\tau = RC$ is not a constant quantity. The deviation of the transient characteristic of the amplifier from an exponential form is associated with the fact that the simple equivalent scheme for the input circuit does not correspond to the true scheme. The reason for this is not only in the distributive nature of the capacity in the

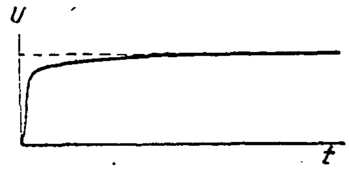

Figure 4. The characteristic form of the transient process with delayed rise at the end.

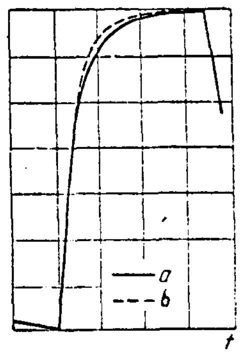

Figure 5. Experimental (solid line) and design (broken line) curves for the transient processes in an amplifier without compensation.

feedback network C, but also depends on the time of distribution of the volume charge in the dielectric of the ceramic forms and glass shells of high megohm resistances.

The shape of the transient characteristic of the amplifier with compensation in the negative feedback loop may be improved substantially without increasing the capacity in the feedback loop. For this purpose it is necessary to introduce another compensation parameter into the scheme - the maximum capacity C_D which shunts the resistance R_K. The compensation scheme with additional capacity is shown on figure 6. The variation of current sensitivity as a function of frequency for the scheme with additional capacity has the following form:

$$\dot{\rho}(\omega) \approx \frac{R(1 + j\omega\tau'_{K})}{1 + j\omega\tau' - \omega^2(K^{-1}\tau'_{K}\tau_{\Sigma} + \tau\tau_{D})},$$

where $\tau' = \tau + \tau_D$, $\tau'_K = \tau_K + \tau_D$, $\tau_D = R_K C_D$. This expression has the same structure and the same order of the polynomial in the denominator as the scheme without C_D but has other values of coefficients for $j\omega$ and $-\omega^2$. By replacing $j\omega$ with p and setting the denominator $\bar{\rho}$ (p) equal to zero, we obtain the characteristic equation of the scheme

$$p^2 + p\frac{\tau'}{K^{-1}\tau'_{K}\tau_{\Sigma} + \tau\tau_{D}} + \frac{1}{K^{-1}\tau'_{K}\tau_{\Sigma} + \tau\tau_{D}} = 0.$$

The time constants of the two exponents which comprise the transient characteristic are associated with the roots of the characteristic equation by the well-known relationships: $\tau'_{\sigma} = -p_1^{-1}$, $\tau'_M = -p_2^{-1}$.

During the experimental verification of the scheme the values of C_D which were measured provide for the best form of the transient characteristics for the minimum t_{front} (figure 3c). From the known parameters of the scheme the values of the coefficients of the characteristic equation were computed and its roots were determined. By comparing the coefficients of the characteristic equation for a scheme with and without the additional capacity, it was shown

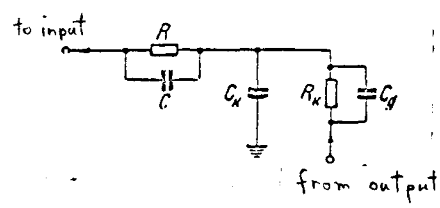

Figure 6. The schematic diagram of the compensating network with additional capacity C_D.

that when C_D was introduced, the root p_2 and the recriprocal quantity τ_M remained almost unchanged. The other root p_1 decreases and the time constant τ_σ increases by a factor of approximately 1.5. In this case there is also an increase in the rise time t_{front} which is measured at the level 0.63 U_{max}. The increase in t_{front} may be compensated by an increase in C_K and a corresponding one in τ_K which no longer distorts the form of the transient process when C_D is present. By selecting the values of capacities C_K and C_D we may obtain almost the same rise time that we have when C_D is absent but with a monotonic transient characteristic without the slow rise time. The values t_{front} for two values of R were obtained after the introduction of additional capacity into the scheme as shown on Table 1. By comparing the forms of the transient characteristics with C_D and without it (figure 3c and d) we see that the additional capacity increases the rise time of the output voltage compared with the ideal exponential curve for $t > t_{front}$. Without C_D for $t > t_{front}$, on the other hand, we observe a decrease in the rise time compared with the ideal exponent curve. The improvement in the form of the transient characteristics occurs because the low percentage feedback which is retained due to capacity C_D turns out to be positive. A schematic with two independent compensation parameters C_K and C_D, which is described by an equation of the second order, provides for a more accurate compensation of the true scheme than the scheme with one parameter C_K which, under the condition $\tau_K = \tau$, is described by an equation of the first order. /92

In the practical realization of the compensation scheme a substantial role is played by the manner of packaging. To decrease the parasitic feedback through distributed capacities the feedback network must be well shielded. The amplifier must be designed and constructed in such a way as to provide for a large value of the bandwidth-frequency product Kf_c in the feedback loop. The quality of compensation also depends on the type of high megohm resistance. As we can see from Table 1, resistances KVM are better than KLM.

The compensation scheme with additional capacity was checked out not only on the bread-board but was used in models of wide-band electrometric amplifiers constructed for experimental purposes. The results which have been described above were reproducible. The basic characteristics of a carefully constructed sample with a gain of $K = 500$ and a limiting frequency of 1500 cps operating with a resistance $R = 10^{11}$ ohm and an input capacitance of $C_{in} \approx 10$ pf are shown in the last line of Table 1. A rise time of $t_{front} = 1.5$ milliseconds was achieved and an upper limiting frequency of $f_{0.7} = 150$ cps. The equivalent capacity of the input circuit in this case is equal to $C_e \approx t_{front}/R = 0.015$ pf, while the design input capacity is $(C_{in} + C)/K = \tau_\sigma^*/R = 0.022$ pf. In this sample a further decrease in t_{front} is limited by the value of K. An introduction of additional capacity not only provided for a good form of the transient characteristic but also made it possible to slightly decrease the rise time.

2. Compensation by Means of Positive Feedback.

The principal scheme of compensation is shown in figure 7. The additional positive feedback is provided through the capacity $C_+ = 0.1 - 0.5$ pf to the input at the same point where we feed the principal negative feedback. To vary the phase of the output voltage U and to control the percentage of positive feedback the latter is taken from the output through a passive or active β-network (usually $\beta < 1$). In practice, β-network may be realized, e.g., in the form of a plate-follower or a small resistance in the cathode or emitter of the final stage with a plate or collector load. The other elements of the

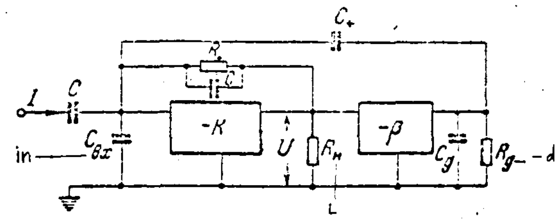

Figure 7. The principal scheme of compensation by using positive feedback.

scheme in figure 7 are the same as shown in figure 1 if we remove the compensating filter from the latter.

The frequency characteristic of the current sensitivity for the scheme in figure 7 is given by the expression:

$$\dot{\rho}(\omega) = \frac{\dot{U}}{\dot{I}} = \frac{K}{1+K}\frac{R}{1+j\omega(\tau_\Sigma - \tau_+)} \approx \frac{R}{1+j\omega(\tau_\Sigma - \tau_+)},$$

where

$$\tau_\Sigma = R[C + (C_{BX} + C_+)/(1+K)] \approx R[C + K^{-1}(C_{BX} + C_+)];$$
$$\tau_+ = K\beta RC_+/(1+K) \approx \beta RC_+.$$

The transient characteristic of the scheme is:

$$\rho(t) = U(t)/I_0 = R(1 - \exp[-t/(\tau_\Sigma - \tau_+)]).$$

Due to positive feedback the equivalent capacity of the input circuit $C_{equi} \approx C + K^{-1}(C_{in} + C_+) - \beta C_+$ may be positive as well as negative. If $C_{equi} < 0$ the scheme becomes unstable.

The experimental investigation of the circuit carried out on the same breadboard using the same resistances R as in the case of compensation in the /93 negative feedback loop, showed that the transient process in this case is not described by one exponential curve. As we see from figure 8 (which shows the oscillograms of the transient process), with a small amount of feedback, the transient characteristic is monotonic (figure 8a). As the amount of positive feedback is increased, damped natural oscillations occur (figure 8b) which are characteristic for networks described by equations of second or higher order. As the feedback is increased, further oscillations occur whose form is close to sinusoidal. As in the case of compensation according to ref. 1, all these phenomena are associated with the fact that the true schematic of the input circuit without compensation is not described with sufficient accuracy by the simple equivalent scheme and the equation of first order.

Table 2 shows the results of testing the compensation produced by positive feedback. The capacity for positive feedback for all values of R was the same: $C_+ = 0.13$ pf. Although the time constant with compensation $\tau_{equi} = \tau_\Sigma - \tau_+$ computed from the parameters of the scheme turns out to be close to the measured rise time ($t_{front}/\tau_{equi} = 1.8$-$1.2$), the effect of compensation is small (with resistances KLM t_{front} with compensation less than the noncompensated τ only by 25 to 30 percent). Compensation is not very effective because the

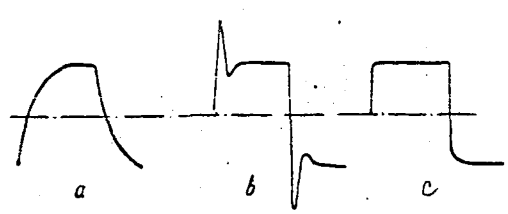

Figure 8. The forms of the transient process in the scheme of figure 7 with various amounts of positive feedback.

TABLE 2

R, ohm	Without compensation: τ, milli-sec	Without compensation: C, pf	With compensation without C_D: β	With compensation without C_D: t_{front}, milli-sec	With compensation without C_D: $f_{0.7}$, cps	According to calculations must be: $t_{equi}=\tau_{-}\sum\tau_{+}$, milli-sec	According to calculations must be: t_{front}/τ_{equi}	Effectiveness of compensation: τ/t_{front}	Compensation with additional capacity: C_D, pf	Compensation with additional capacity: t_{front}, milli-sec	Compensation with additional capacity: $f_{0.7}$, cps	Compensation with additional capacity: $C_{equi}=t_{front}/R$, pf	Effectiveness of compensation: τ/t'_{front}
$4\cdot10^{10}$	4	0.10	0.30	2.0	80	1.1	1.8	2	—	—	—	—	—
$1\cdot10^{11}$	20	0.20	0.23	16	10	15	1.1	1.25	1500	3.2	50	0.032	6
$9\cdot10^{11}$	240	0.25	0.35	180	0.9	150	1.2	1.33	40000	50	3.2	0.055	5
$1\cdot10^{12}$	85	0.08	0.35	14	11	8	1.8	6	—	—	—	—	—

amount of positive feedback is small while a further increase in β causes the form of the transient process curve to become highly distorted.

To increase the effectiveness of compensation an additional compensation parameter was introduced into the scheme--a small capacity C_D shunting the output resistance R_D of the β-network (figure 7). This capacity which shunts the resistance R_D at high frequencies decreases the amount of positive feedback and slightly shifts its phase. The equation which describes the scheme with C_D is of second order:

$$\dot{\rho}(\omega) = \frac{R(1 + j\omega\tau_{д})}{1 + j\omega(\tau_{э} + \tau_{д}) - \omega^2\tau_{\Sigma}\tau_{д}},$$

where $\tau_D = R_D C_D$. It contains two independent compensation parameters β (or C_+) and C_D which, if properly selected, make it possible to obtain a good form for the transient characteristic (figure 8c) with a small rise time. In the last column of Table 2 we show that when C_D is introduced it is possible to increase the effective compensation τ/t_{front} from 1.25 to 5-6.

Conclusions

A comparison of quantities t_{front} presented in Tables 1 and 2 shows that both methods of compensation produce almost the same results when we apply additional capacities. This conforms with the established rule, since the effectiveness of compensation depends not on the type of scheme but on the order of the equation which describes it and on the allowable number of independent compensation parameters.

The decrease in the rise time is limited by the following: in the first place by the value of the gain in the feedback loop K and its dependency on /94
frequency; in the second place on the parasitic feedback loops; in the third

place on the non-exponential charging—discharging processes in the distributed capacity of resistance R. The noticeable difference in the quantities t_{front}, obtained with resistances of various types points to the necessity of a further improvement in the construction and production methods for high megohm resistances.

In the investigated amplifiers we obtained a minimum rise time of t_{front} = 1.5 milli-sec for R = 10^{11} ohm which corresponds to C_{equi}= 0.015 pf. The decrease in t_{front} was limited by the small value K = 500. In the literature there are descriptions of amplifiers with compensation in which by increasing K to $10^4 - 5\cdot10^5$ the equivalent input capacity C_{equi} of the circuit was decreased to 0.002 pf (ref. 2) and 0.006 pf (ref. 6). Apparently this limit depends on the nature of the distributed capacity of resistance R.

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